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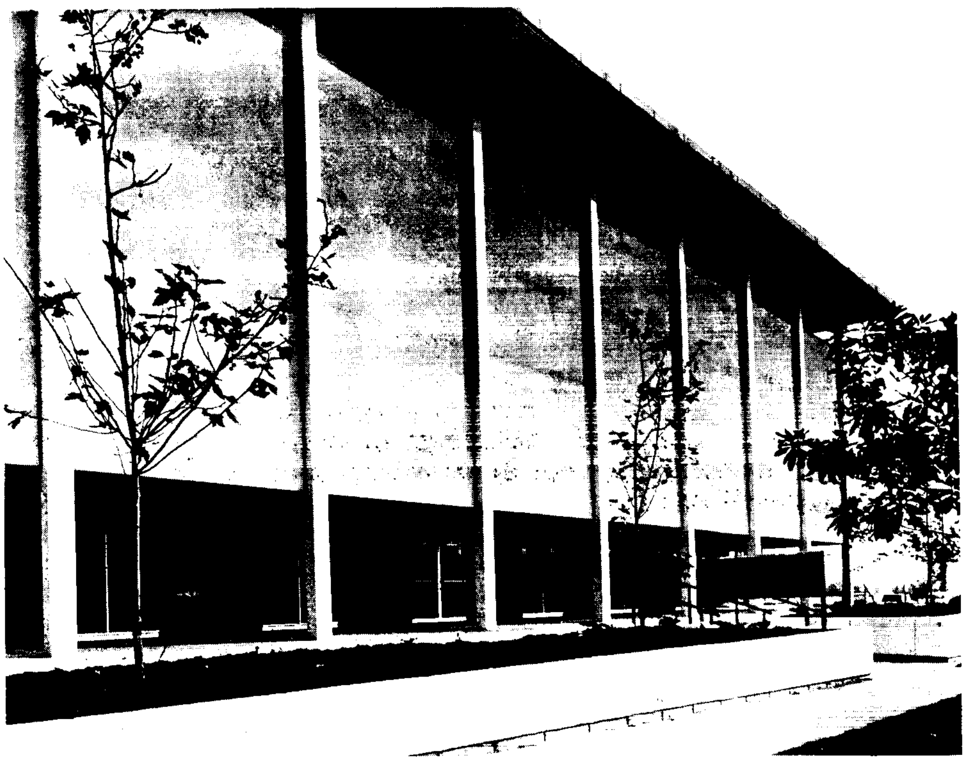

RE-ORDER NO. 65-287
VOL. I

Final Report

ANALYSIS OF ANCILLARY EQUIPMENT FOR SOLAR-THERMIONIC SYSTEM

Prepared for
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California
Attention: R. Boring

Contract 950699 - Task III

EOS Report 4326-Final 10 March 1965

Volume I: Summary

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ELECTRO-OPTICAL SYSTEMS, INC. — PASADENA, CALIFORNIA

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VOLUME I: SUMMARY

1. INTRODUCTION

This final report describes the results of an analysis of solar-thermionic systems performed under JPL Contract 950699 during the period 9 September 1964 through 30 January 1965.

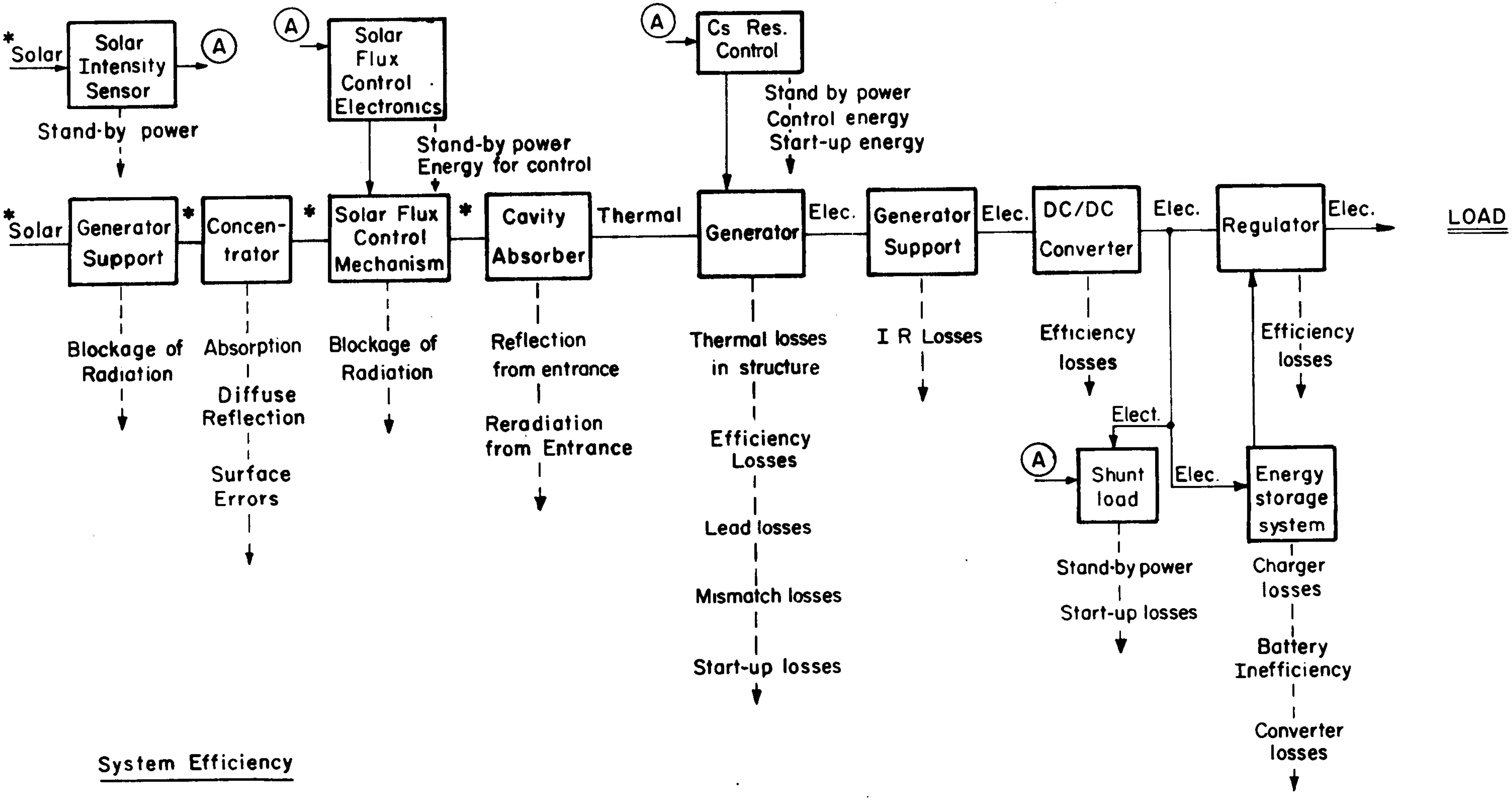
The text is divided into two parts; the first part, Volume I, is a summary of analysis results and recommendations. Volume II contains the detailed analysis and is divided according to technical areas.

The principle objectives of the program were to accomplish:

1) A summarization of the present status of principle components of a solar-thermionic systems; concentrator, generator, and thermionic converter.
2) An analysis and optimization of the control and ancillary components needed as a function of typical mission requirements, anticipated load profile and desired overall system efficiency.
3) A prediction of system performance based on the evaluation of components and component parameters.
4) Recommendations for future component design.
5) An outline of remaining development steps necessary to bring these components to flight status.

2. SYSTEM OPERATION

Figure 1 illustrates the components and subsystems which must be considered in the design of a practical solar-thermionic system. Also shown are the major sources of energy loss in the system, and an overall equation which describes system efficiency. Instrumentation will be provided in many places but is not shown specifically in Fig. 1.



System Efficiency

$$\eta_{sys} = \underset{\text{Obscuration}}{\underline{\eta_{abscr}}} \times \underset{\text{Concentrator-Absorber Efficiency}}{\underline{\eta_{c\text{-}a}}} \times \underset{\text{Generator Efficiency}}{\underline{\eta_{gen}}} \times \underset{\text{Lead eff.}}{\underline{\eta_{lead}}} \times \underset{\text{DC/DC Converter Efficiency}}{\underline{\eta_{conv}}} \times \underset{\text{Regulator Efficiency}}{\underline{\eta_{reg}}} \times \underset{\text{Control Efficiency}}{\underline{\eta_{cont}}}$$

$$\times \frac{1}{1 + K/\tau_L \; \eta_{stor}}$$

(K = Factor depending on time in dark, peak power, start-up time, etc.
τ_L = Light time η_{stor} = Storage efficiency)

FIG. 1 - SOLAR-THERMIONIC SYSTEM BLOCK DIAGRAM AND ENERGY LOSSES

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More details concerning the scope of the study and ground rules of the analysis are contained in Section 1, Volume II.

As a result of the systems analysis study, a series of programs has been recommended by EOS as being of primary importance in the development of high efficiency, reliable solar-thermionic systems. Twenty-eight programs are discussed in Section 11, Volume II.

3. SYSTEM WEIGHT

Table I is a summary of system component weights as they apply to different power levels and selected missions. These weights resulted from analysis performed under the study program and are given here as being representative of the system weight that can be achieved by prototypes in 1966-67. Weight and efficiency numbers are based on reasonable projections of the state-of-the-art as described in Volume II. As a rule of thumb, for the same power output, the specific weight of the system at Mars (50 w/ft^2) will be about twice that of the system at Earth, while the specific weight of the system at Venus (250 w/ft^2) will be about 2/3 the system weight at Earth. Due primarily to lower generator efficiences, a system using 1965 state-of-the-art components would weigh roughly 2.5 times the 1968 system. System weight may drop by 10 to 20 percent from 1968 to 1970.

4. SOLAR CONCENTRATOR

Projected concentrator characteristics are illustrated in Fig.2 which shows the lbs/sq ft and projected efficiency characteristics of solar concentrators. In the 1968-70 period, specific weights of 0.5 lb/ft^2 for nickel concentrators and 0.3 to 0.4 lb/ft^2 for aluminum and beryllium concentrators are believed possible.

Principle problem areas in concentrator development are:

1) Development and test of a highly specular reflective surface and demonstration that it will withstand the space environment.

TABLE Ia

ESTIMATED SYSTEM PERFORMANCE PARAMETERS (1965)

Mission	1000 n. mi. Sun Synchronous Earth Satellite					
Percentage of Light	100 percent					
Distance from Sun	1 AU					
Solar Intensity (w/ft^2)	130					
Concentrator Diameter (ft)	4	5	6	7	8	9-1/2
Efficiency (percent)						
Collector-Absorbert Efficiency	54	57	59	61	62.5	63.5
Generator Obscuration and IR Efficiency	95	96	96.3	96.5	96.8	97
Generator Efficiency	12	12	12	12	12	12
Power Conditioning Efficiency	70	74	76	77	77	78
Control Efficiency	-	-	-	-	-	-
System Efficiency	4.1	4.9	5.2	5.4	5.6	5.8
Power Output (Watts)	67	125	191	270	372	534
Weight (lb)						
Concentrator	6.4	10	14.4	19.6	25.6	36.2
Generator Support	2.4	3	4	6	8	10
Generator	1.2	3.1	4.5	6.7	9	12.4
Power Conditioning	10	12	14	16	19	22
Control Wt.	-	-	-	-	-	-
System Wt. (lb)	20	28.1	36.5	48.3	61.6	80.6
System Specific Wt. (lb/KW)	298	225	191	179	166	153
System Power Density (w/ft^2)	5.4	6.4	6.8	7.0	7.4	7.6

Assumptions:

1) Cavity Temperature of 1700°C.
2) Concentrator specific Wt. = 0.5 lb/ft^2 assuming Ni concentrators.
3) The most simple system is assumed:
   a) Steady-state conditions
   b) No energy storage
   c) No Cs Res. or solar flux controls
4) Weight for auxiliary attachments to vehicle not included.
5. Weight for instrumentation not included.
6) Performance is based on judgement of performance available from prototype components demonstrated as of March 1965.

TABLE Ib

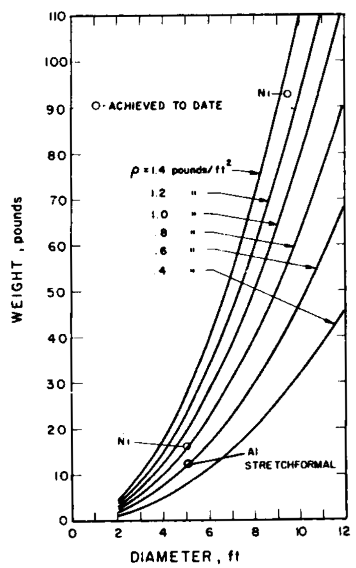
ESTIMATED SYSTEM PERFORMANCE PARAMETERS (1968)

Mission	1000 n. mi. Sun Synchronous Earth Orbiter					
Percentage of Light	100 percent					
Distance from Sun	1 AU					
Solar Intensity (w/ft^2)	130					
Concentrator Diameter (ft)	4	5	6	7	8	9-1/2
<u>Efficiency</u> (Percent)						
Collector-Absorber Efficiency	54	57	59	61	62.5	63.5
Generator Obscuration and IR Efficiency	95	96	96.3	96.5	96.8	97
Generator Efficiency	18	18	18	18	18	18
Power Conditioning Efficiency	76	77	77.8	78.5	79.2	80
Control Efficiency	-	-	-	-	-	-
System Efficiency	7.0	7.6	7.9	8.3	8.6	8.8
Power Output (Watts)	114	194	291	415	551	811
<u>Weight</u> (lb)						
Concentrator	5.1	8	11.5	15.7	20.5	29
Generator Support	1.2	1.5	2	3	4	5
Generator	1.5	2.8	4.0	5.2	7.1	10.4
Power Conditioning	6	8	11	14	16	21
Control Wt.	-	-	-	-	-	-
System Wt. (lb)	13.8	20.3	28.5	37.9	47.6	65.4
System Specific Wt. (lb/KW)	121	104.5	98	91.3	84.7	74.1
System Power Density (w/ft^2)	9.9	10.0	10.1	10.3	10.5	10.8

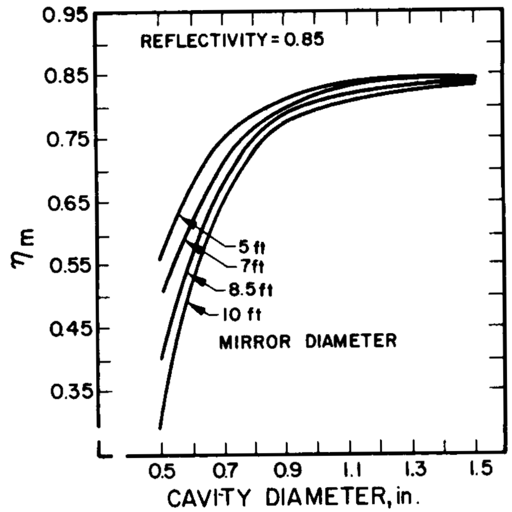
<u>Assumptions</u>:

1) Cavity temperature of 1700°C.
2) Concentrator Specific Wt. = 0.4 lb/ft^2 assuming Al concentrators.
3) The most simple system is assumed:
   a) Steady-state conditions
   b) No energy storage
   c) No Cs Res. or solar flux controls
4) Weight for auxiliary attachments to vehicle not included.
5) Weight for instrumentation not included.
6) Performance is based on reasonable judgement of performance available in prototypes in 1966-67, system availability in 1968.

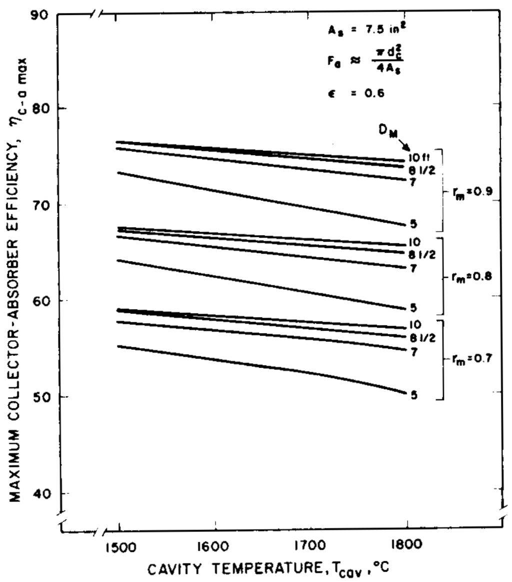
FIG. 2 - CONCENTRATOR CHARACTERISTICS



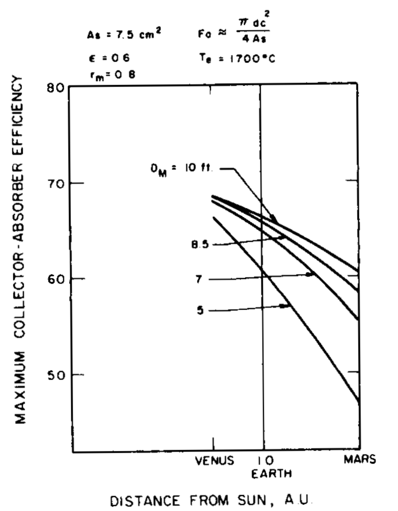
Mirror Diameter vs Weight



Mirror Efficiency



Maximum Collector-Absorber Efficiency at Earth



Maximum Collector-Absorber Efficiency at Venus, Mars, Earth

2) Optimization of weight characteristics through analysis and test to determine limits on concentrator weight; also, development of concentrators with new materials.
3) Determination through analysis and test of the proper support mechanisms.

A survey was made of available data regarding surface degradation. It was not found possible to derive accurate estimates of degradation but sufficient evidence is available that indicates a severe problem may exist due to U.V. and micrometeoroid degradation.

Calculations were made to establish the efficiency of the concentrator-absorber under a variety of conditions. Expression for concentrator-absorber efficiency is shown in Fig. 2 as a function of cavity temperature and distance from the sun. Reflection and reradiation losses from the cavity are both significant with reflection losses being predominant. Assumptions for mirror efficiency are shown.

Because of reflection and reradiation losses, it was found that the concentrator-absorber efficiency (2c-a) could be higher for larger concentrators even though the surface deviations were greater. The curves of Fig.2-d are somewhat pessimistic at Mars and optimistic at Venus since the change in the sun's image size was not considered.

A series of recommended programs for concentrator development are discussed in Section 11, Volume II of this report. These programs are:

1) Evaluation of Mirror Coatings (by simulated space tests)
2) Establishment of Concentrator Coating Techniques
3) Dynamic Analysis and Test of 5-ft Concentrator Structures
4) Dynamic Analysis and Test of 9-1/2 ft Concentrator Structures
5) Development of 9-1/2 ft, 50^{o} to 60^{o} Rim Angle Masters
6) Investigation and Environmental Test of Al, Be and other Concentrators

7) Development of Rear Surface Coatings for Concentrators
8) Investigation of Techniques for Stiffening Thin Mirror Surfaces
9) Investigation of Torus Attachment Techniques

The two modes of failure of the concentrator of most concern are degradation of the mirror surface during cruise and buckling of the skin (for lightweight concentrators) during launch. Either failure can lead to partial or complete failure through decrease of cavity temperature and loss of power. Methods of compensation include the use of increased concentrator area combined with a solar flux control subsystem.

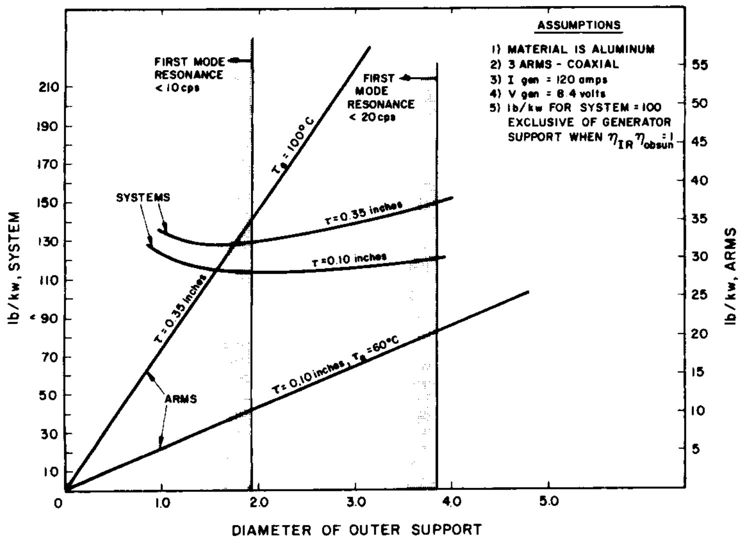
5. GENERATOR SUPPORT

Figure 3 illustrates several generator support concepts which could be used in an operational system. The choice of the number of arms hinging and other methods of integrating the arms into the system will depend on:

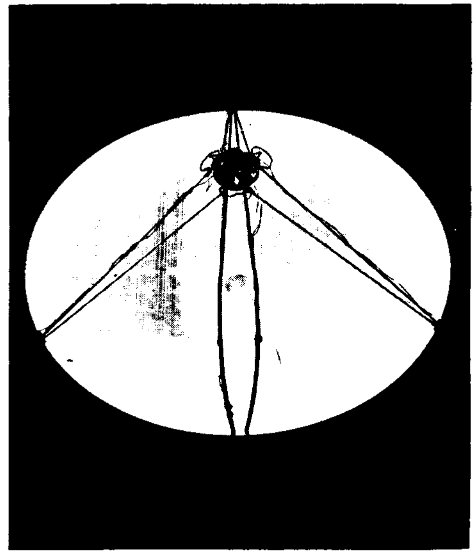
1) Vibration characteristics of the structure
2) Packaging and deployment possibilities
3) Effect on system design

The design of the arms should represent an optimum tradeoff between the following factors:

1) Obscuration of the concentrator
2) Power losses in the leads due to high resistance
3) Amount of heat conducted to the DC/DC converter at the end of the arms
4) Ability to accurately place the generator without movement due to thermal gradients
5) Minimum weight
6) Ability to hold instrumentation, leads, etc.
7) Elimination of magnetic field



Typical Generator Support Optimization



Rigid, Coaxial, 3-Legged Support Structure

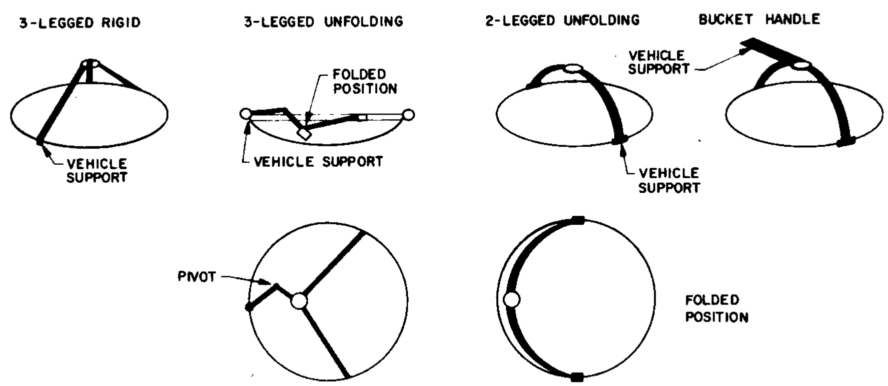


FIG. 3 - GENERATOR SUPPORT

From a systems viewpoint, a serious problem is the conductivity of heat down the relatively thick leads to the DC/DC converter. Temperatures above $50^{\circ}C$ at the DC/DC converter will result in lower efficiencies and reliability.

Two sets of support arms, each for 5 ft concentrators, have been assembled. The first was a 3-legged aluminum frame structure which unfolded into position. The second was a rigid 3-legged structure using coaxial members shown in Fig. 3. The arms shown in Fig. 3 are made of aluminum; the entire structure (including concentrator) has been subjected to the Atlas-Agena D, Mariner Mars, solar panel complete Type Approval level environmental tests. The generator support arm structure has been subjected to Saturn IB Type Approval acoustic noise (148DB) tests without failure or damage.

The choice of materials was examined and it was found that beryllium would provide the best support arms when all design restrictions were considered. An example of system tradeoffs is shown in Fig. 3 which shows the effect of varying the diameter of the support arms on system weight.

In all cases examined, optimum generator support weight was found to be fairly light, ranging from 2.5 lbs for a 5 ft system to 4.2 lbs for a 9-1/2 ft system. The length of the support arms as a function of concentrator diameter is shown in Fig. 4.

The failure mode of concern is the ability to unfold the arms reliably. This could lead to partial or complete failure; compensation could take the form of extra override mechanisms to insure unfolding.

Recommended programs for generator support development are:

1) Design and Development of Unfolding Generator Support Arms for a 5 ft System
2) Design and Development of Rigid Generator Supports for a 5 ft System
3) Optimization of the Generator Support Design

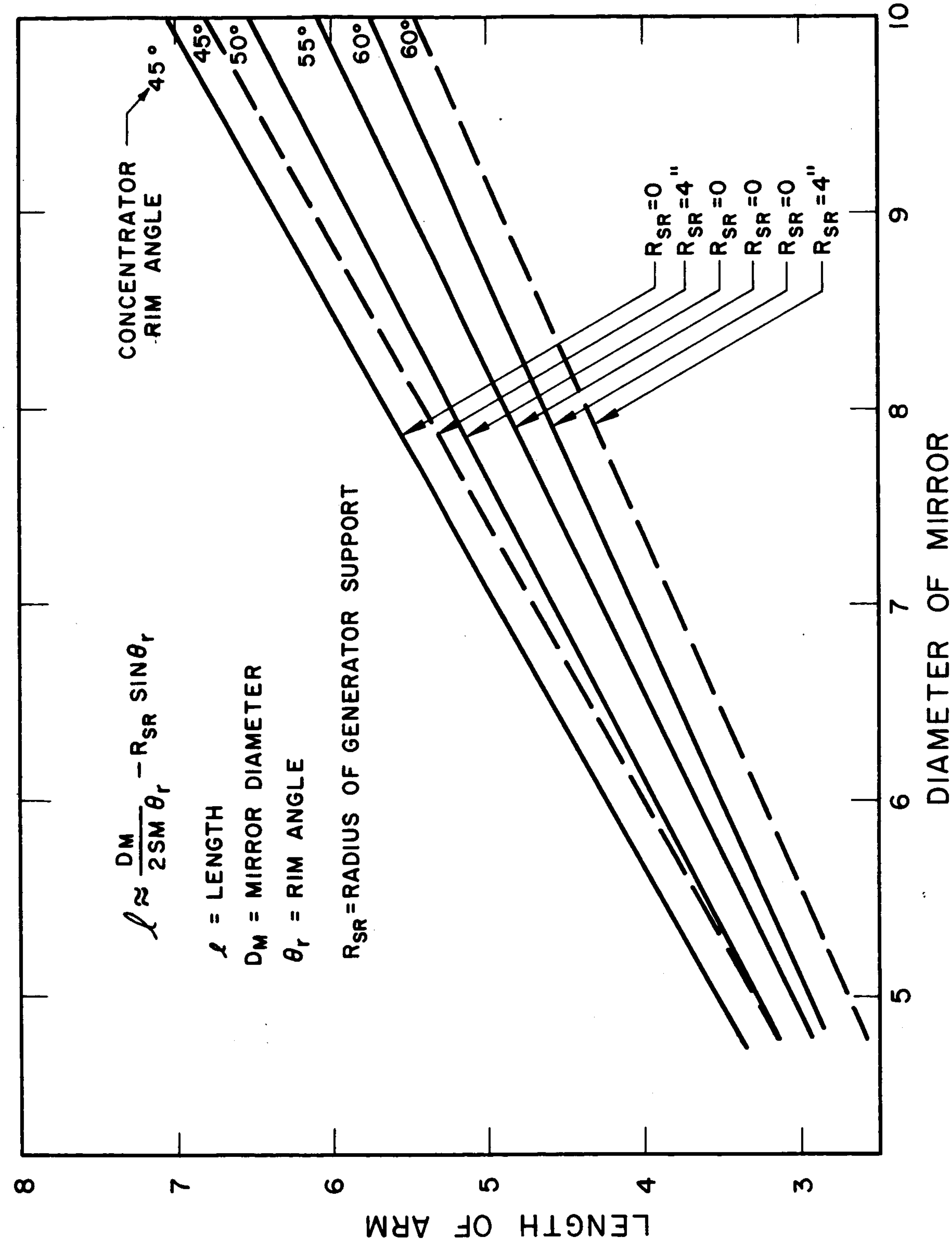


FIG. 4 - LENGTH OF GENERATOR SUPPORT ARM

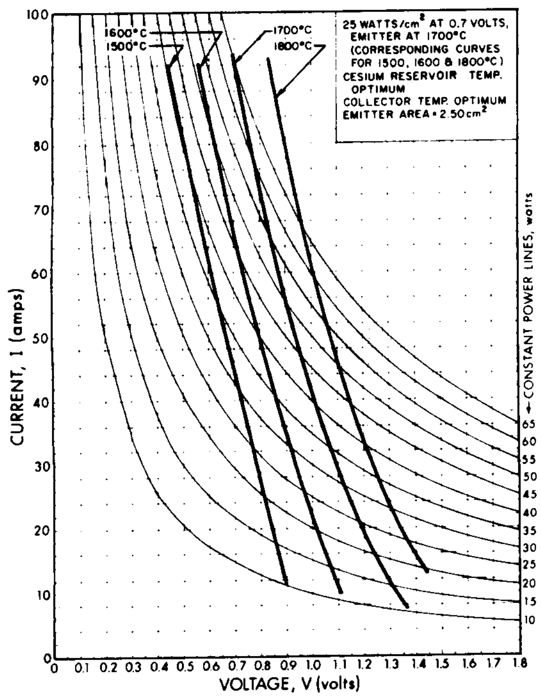
6. THERMIONIC CONVERTER

During the study, I-V, P-V and efficiency curves were derived for converters operating at 15, 20 and 25 watts/cm^2 at 0.7 volts and emitter temperatures of 1500 to 1800°C. Typical curves are shown in Fig. 5 . The converters were assumed to be operating in an excited mode.

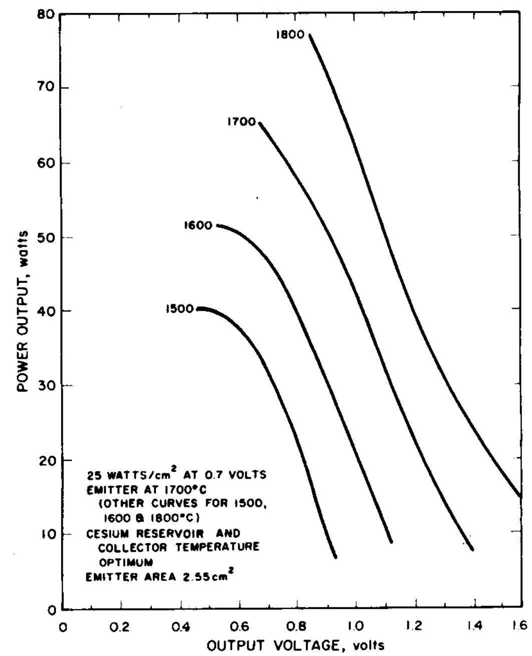
As illustrated in Fig. 5-c, several different types of I-V curves can be derived depending on power input conditions. Almost all the converter I-V curves measured in the laboratory maintained conditions of constant emitter temperatures and "optimized" reservoir and radiator temperatures. This type of curve, while useful as an indication of potential performance, cannot be used in systems analysis where constant power input is the governing condition in converter operation.

If a converter is designed for 1700°C emitter temperature at a specific voltage, operation at other voltage levels with constant power input will vary the temperatures within the converter. Higher currents and lower voltage results in higher seal and collector temperatures. Lower currents and higher voltage results in higher emitter temperature and lower collector and seal temperature. Until adequate reliability data is gathered regarding the effects of varying the load, it is assumed that the optimum design condition from a system viewpoint is to maintain the output of the converter close to the design point.

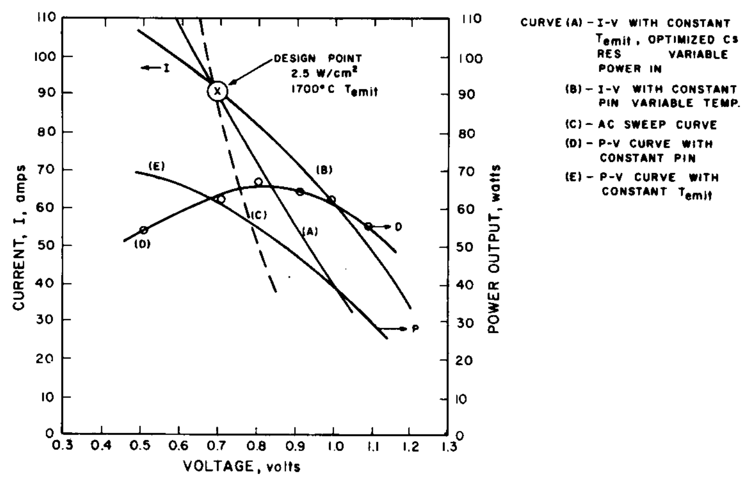
Generally, the avoidance of rapid increases or decreases in temperature is desirable. Also, laboratory tests indicate that start-up will require load adjustment to short-circuit conditions along with a maximum input of solar energy to the generator.



a) Typical I-V Characteristics



b) Typical P-V Characteristics



c) Types of Converter Characteristics

FIG. 5 - THERMIONIC CONVERTER CHARACTERISTICS

Several converters are now available which have exhibited power densities of 20 to 25 w/cm^2 at $2000^\circ K$ and 0.7 volts. It is expected that prototype production diodes exhibiting 25 w/cm^2 will be available by 1966. Weights on the order of 0.5 lb/diode are expected. Principle problem areas are heat transfer through the diode and obtaining low collector work functions.

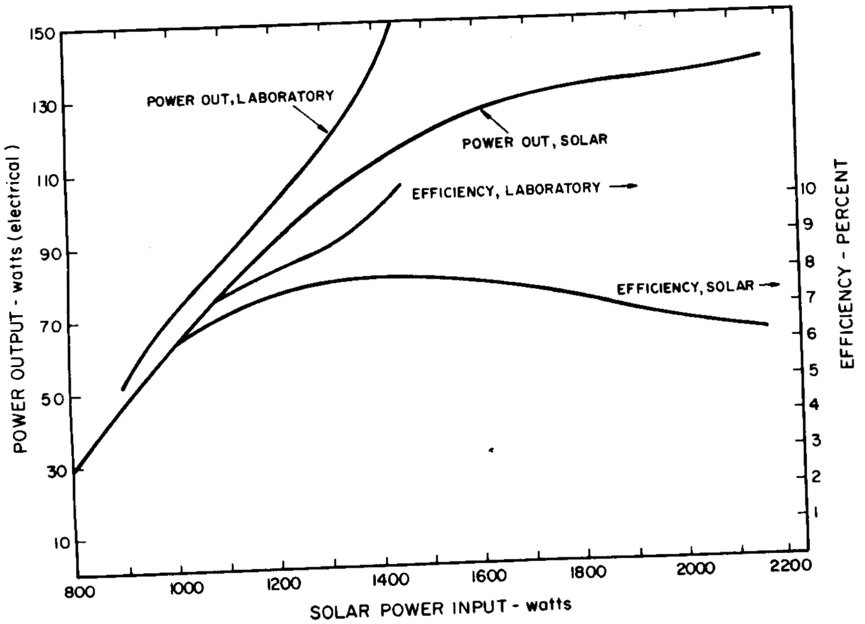
The mechanisms of converter failure are not completely understood. Several converters have been life-tested 5000 hrs at levels of 10 w/cm^2 and several others have been cycled 2000 times. Converter failures can take the form of opens, shorts or partial failure. Compensation can include extra DC/DC converters with failure sensing and shunt mechanisms, and/or extra converters and generators.

Recommended programs for future converter development are:

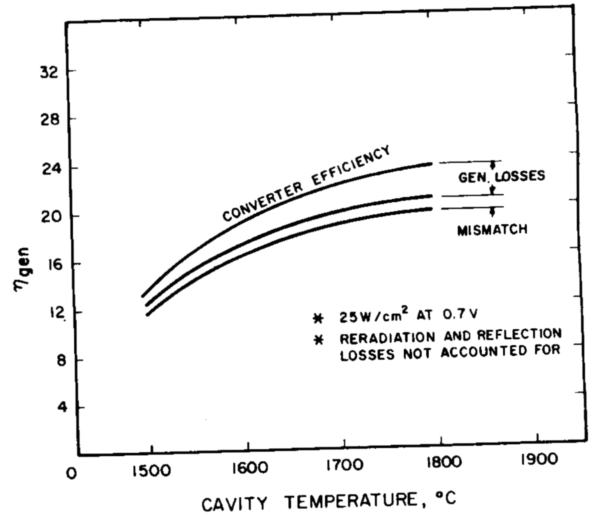
1) High Power Density Diode Advanced Heat Transfer Program
2) High Power Density Material Development Program
3) Thermionic Converter and Generator Life-Testing Program
4) Acquisition of Diode Application Data
5) Investigation of Effect of Lower Temperatures on Converter Design

7. THERMIONIC GENERATOR

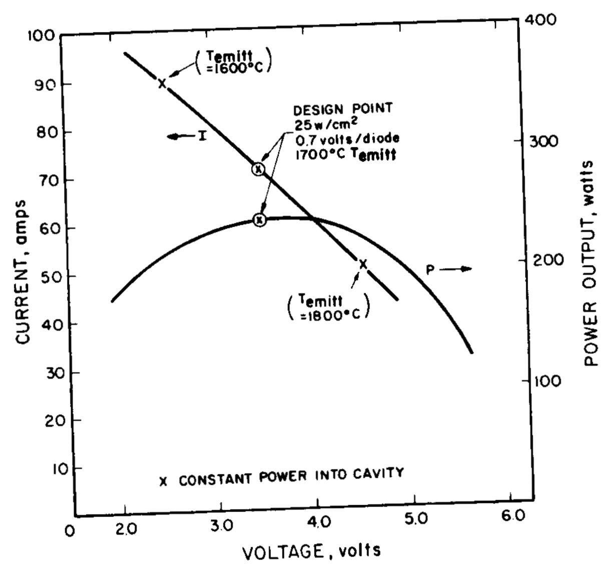
The thermionic generator consists of the thermionic converters, structure for holding the converters, cavity, power leads, front cone and shielding, instrumentation, attachments to the generator support, and related items. Flux controls and cesium reservoir controls may also be attached. The power and efficiency of a 5-converter generator tested by JPL in late 1964 is shown in Fig. 6-a. Also shown is a curve of expected generator efficiency vs cavity temperature using a converter capable of 25 $watts/cm^2$ at $1700^\circ C$. The source of generator losses is indicated.



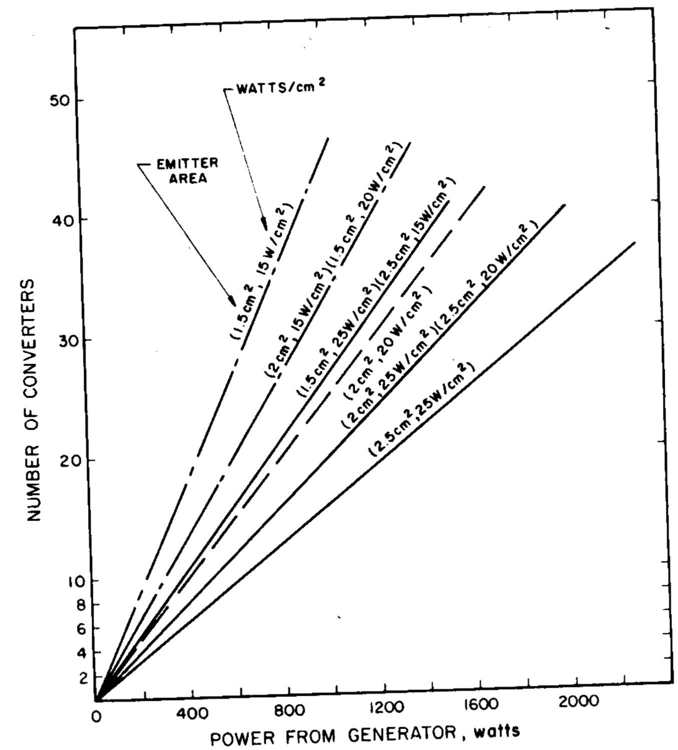
a) Solar and Laboratory Test Data on 5-Converter Generator



b) Generator Efficiency



c) Typical 5-Diode Generator Output Characteristics



d) Number of Converters Required

FIG. 6 - GENERATOR POWER OUTPUT

Parts of the tradeoff in determining systems size and mirror diameter involves a number of converters which will be used in a single generator. The number as a function of power output from the generator is indicated in Fig. 6 .

Generator efficiency does not include the reradiation losses from the cavity. Cavity design is an essential feature, however, of generator design. Reradiation and reflection losses from the cavity can assume major consequences as discussed in Section 5; reflection losses are more serious in general than reradiation.

Detailed studies of generator weight were not made. For systems calculations, it was assumed that each converter would weigh 0.5 lbs with an additional 30 percent for generator structure.

Considerably more effort is required to determine the optimum tradeoffs between generator performance at higher emitter temperatures and the penalty in reliability for operating at non-design point loads.

Recommended programs for generator development are:

1) High Power Multi-converter Design Study
2) Cavity Design and Development

8. INSTRUMENTATION

An examination was made of the types of instrumentation required for operation of the solar-thermionic system and the types of sensors which would be applicable.

Figure 7 illustrates those instruments which are needed for control of the system and which are useful for monitoring performance and/or variation of operational conditions by ground command.

Techniques for measurement are available for all vital functions with the exception of emitter temperatures. Long term stability of thermocouples or resistance elements at emitter temperatures is poor. Passive methods are possible to indicate when temperature levels are passed; these include bi-metallic

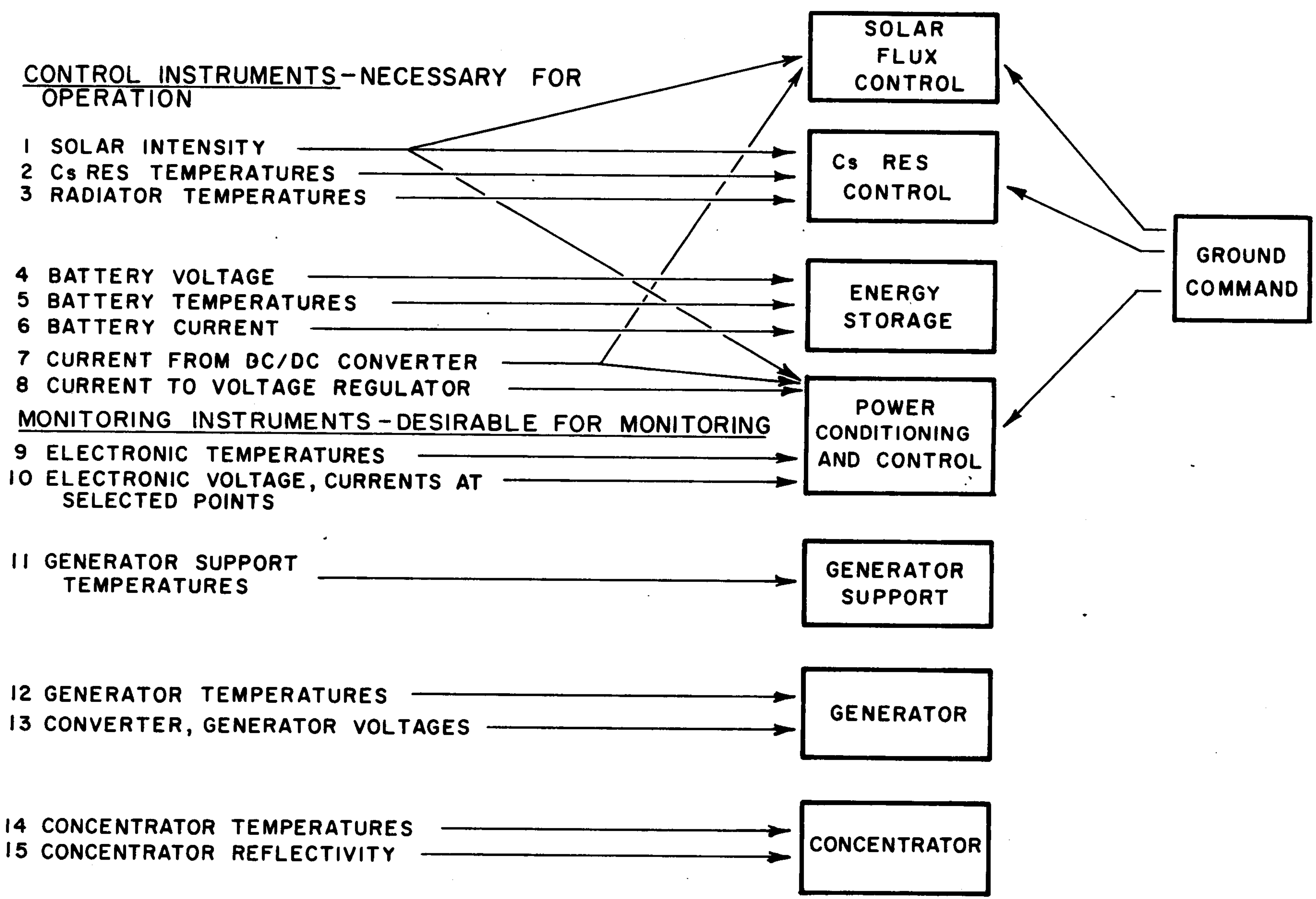


FIG. 7 - CONTROL INSTRUMENTS - NECESSARY FOR OPERATION

elements, melting solids, etc. None of these methods is sufficiently accurate for control purposes. However, it should be possible to extrapolate emitter temperatures from current and voltage measurements of the converter.

Sensing of high current is easily accomplished by a small saturated core circuit. The coil is wound around the DC lead and the current level is sensed by modulation of the coil. Such current sensors will weigh a few ounces and can operate in a relatively high temperature environment. However, long term stability tests are required.

To date, cesium reservoir and radiator temperatures on converters have been measured using thermocouples. It is recommended that resistance elements be developed for use with the converters and eventual use on a flight system. The primary advantages of a resistance element are linearity and lack of extensive backup circuitry. The disadvantage is cost and efforts should be made to develop a low cost unit.

A tradeoff will have to be made between the amount of instrumentation desirable for monitoring. The weight and cabling problems associated with a large number of instruments are further considerations.

9. SOLAR FLUX CONTROL

Solar flux controls would be used for missions which present non-equilibrium conditions to the solar-thermionic system such as orbital darkness, continually increasing or decreasing solar flux, etc. For equilibrium conditions, solar flux control is not required.

For Earth orbital application, solar flux control could be used for the following:

1) Closing off of the cavity entrance during darkness to prevent radiation losses and to maintain higher generator temperatures.

2) Regulation of solar input during start-up to minimize temperature rise rates.

3) Regulation of solar input to account for degradation of the concentrator.

None of the above functions are mandatory from a system viewpoint; i.e., the system will function without solar flux control. Furthermore, the value of solar flux control for the above reasons is doubtful. During darkness, the heat loss from the cavity is a small portion of the heat loss from the rest of the generator. For start-up, laboratory experience indicates that high performance converters will require a maximum of solar input at start-up in order to insure opening of the diode. If severe degradation of a concentrator is expected, the usefulness of the entire solar-thermionic system is in question. On this basis, the use of solar flux control for Earth orbital applications is not recommended. This conclusion might be changed with the introduction of thermal energy storage, or with further data on start-up of converter.

For missions which take the vehicle away from Earth, (planetary and solar probes) solar flux control may be necessary to regulate the input of the solar flux to the generator. Compensation with variable loads or adjustments of cesium reservoir is not possible with large solar intensity variations without considerable overheating of the emitter or seals during one part of the mission. An examination of thermionic converter design to date indicates that seal and emitter temperatures could become extremely high and the reliability of the device would be in question.

The use of load control as a means of compensation for variations in solar flux should not be discarded, however, but should be considered in a separate converter development program with this specific goal in mind.

If some variation in power output can be tolerated, it appears possible to use an entirely "passive" systems; i.e., where regulation of solar flux input to the cavity is obtained by the variation in the focal image directed into a cavity with fixed entrance diameter. Temperature and power poutput variations would occur in the cavity. While the elimination of an "active" flux control is desirable, a "passive" flux control implies a less efficient system and a larger concentrator.

It is recommended that prototypes of the solar flux control mechanisms band electronics be assembled. To date, neither has been accomplished.

Several types of solar flux control mechanisms are illustrated in Fig. 8 . Many types of actuators are available and several types of control inputs can be used. A typical chart showing the effectiveness of "passive" solar flux control is shown in Fig. 9 .

10. CESIUM RESERVOIR CONTROL

The temperature of the cesium reservoir for each individual converter can have a dramatic effect on converter performance. A typical effect is illustrated in Fig. 10 which shows that within a zone of about $\pm$ 10°C, the output power variation is small from a converter at typical operating temperatures.

Laboratory developments to date support the conclusion that in an equilibrium condition, (such as sun synchronous orbiters or solar probes) with no darkness or gross input variations, passive cesium reservoir control can be used. Passive implies the use of no active heater elements to maintain reservoir temperatures but rather the use of conduction and radiation from the converter itself.

However, in a non-equilibrium control situation, (such as Earth orbiters), the use of passive cesium reservoir control will result in non-operative periods while the converters are warming up for periods as long as twenty minutes. Thus, in orbital application, active cesium reservoir control is required while in a probe situation, passive cesium reservoir control will suffice.

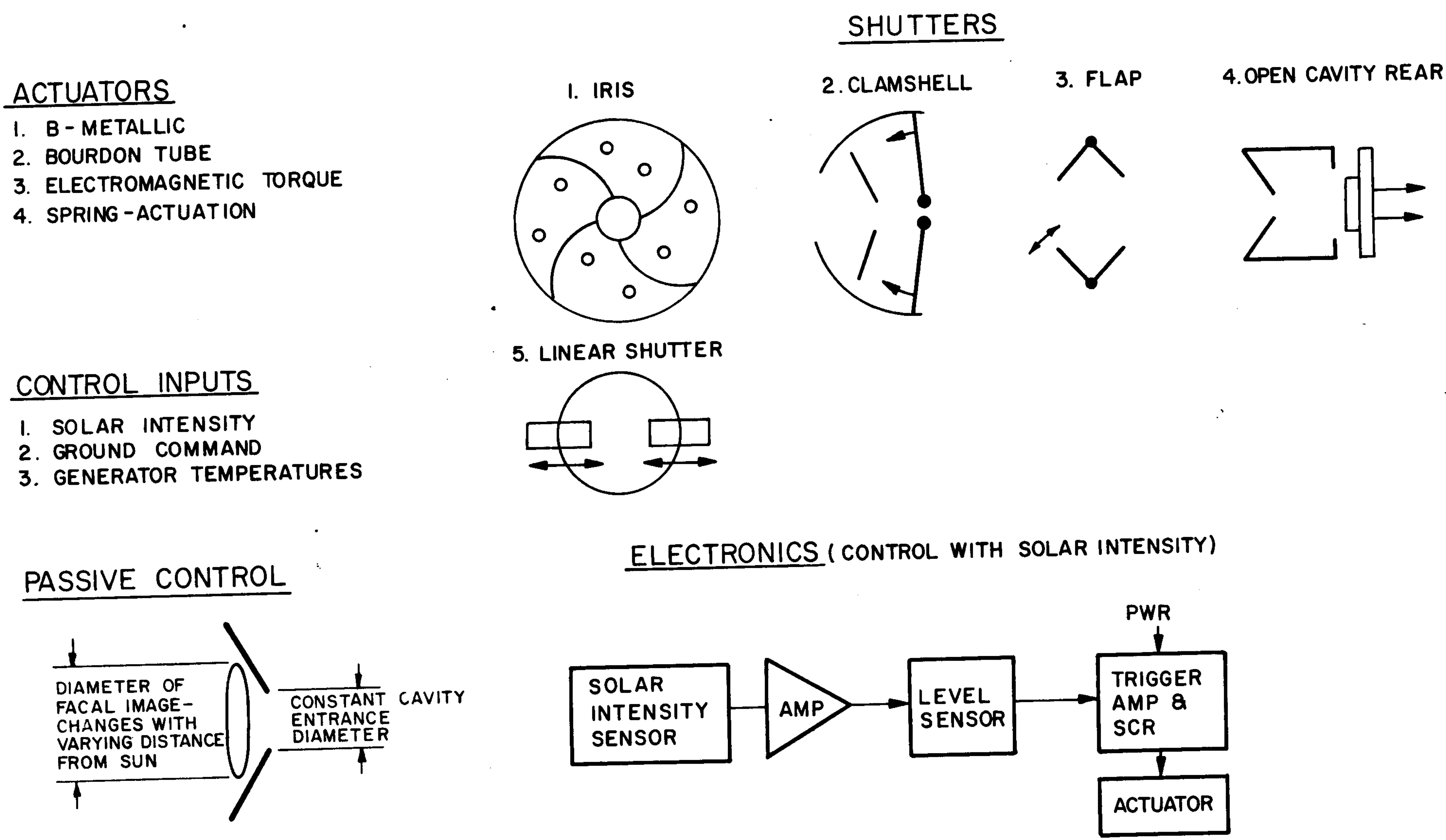


FIG. 8 - SOLAR FLUX CONTROL MECHANISMS

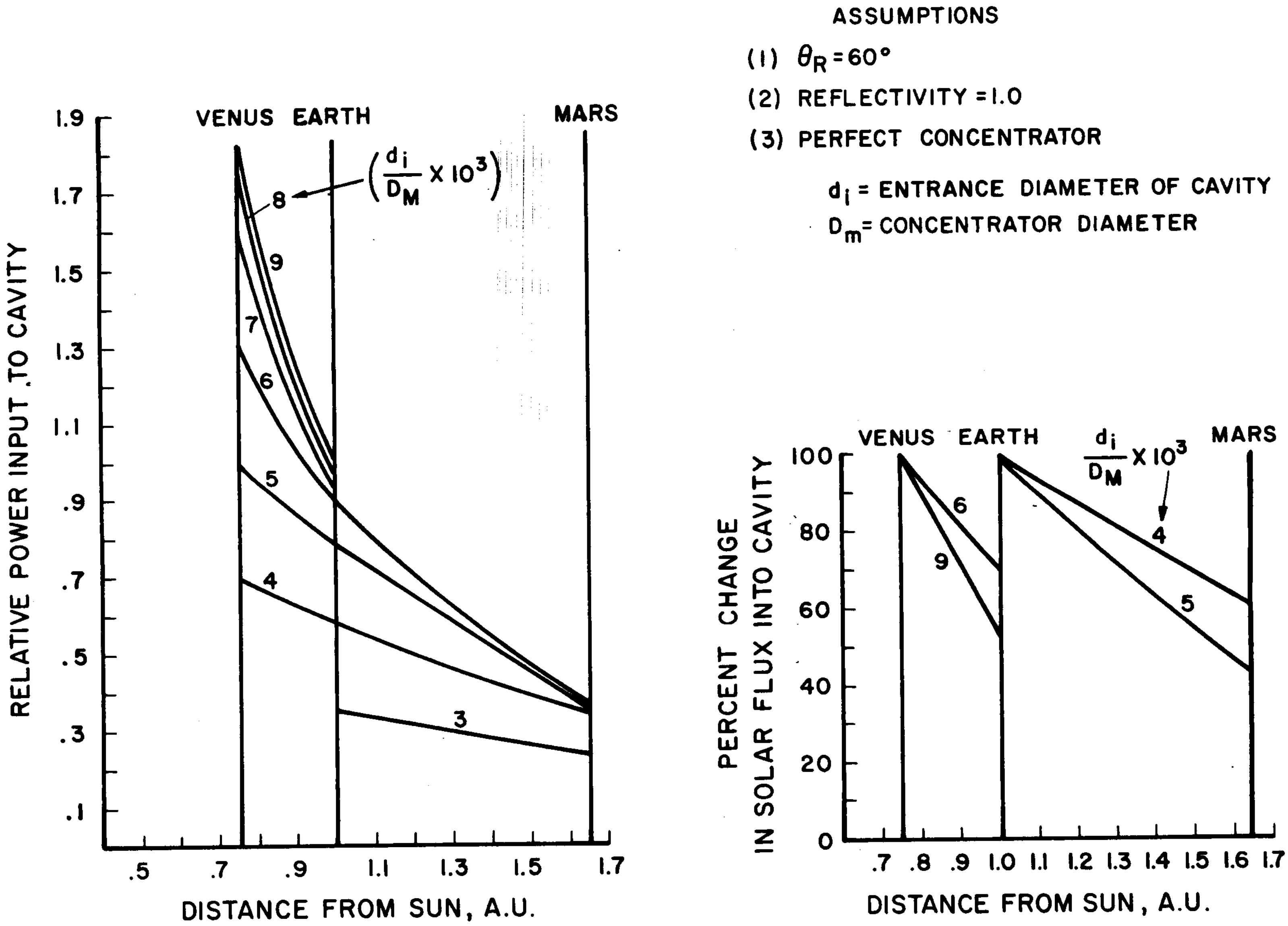


FIG. 9 - PASSIVE SOLAR FLUX CONTROL

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Temperature variations of $10^{o}C$ can be obtained with heater powers of less than one watt. The design of the reservoir would be such that equilibrium temperatures would tend to be somewhat lower than optimum in order to provide positive control.

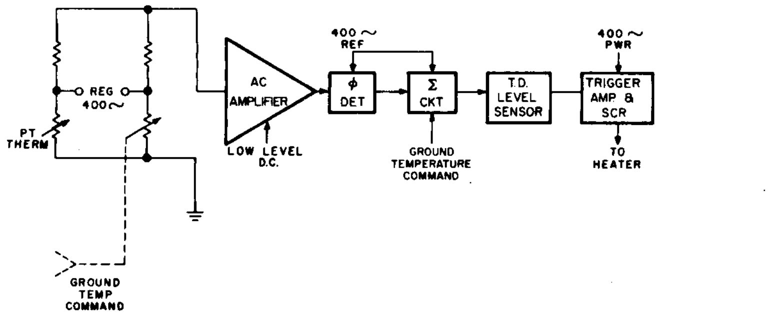
An examination was made of various types of active control circuits which combined reliable operation and extremely low weight. The circuit illustrated in Fig.10 is recommended providing AC power is available from the power system. The entire active cesium reservoir control system for a typical five diode generator would weigh about 12 ounces exclusive of leads from the electronics to the generator.

The influence of active control on generator temperatures is illustrated in Fig. 10 which shows a typical start-up sequence. As shown, the radiator and reservoir, each starting at $100^{o}C$, could consume almost twenty minutes arriving at close to optimum temperatures. It is possible to cut this time in half or less with the use of active heaters. Normally the active heater would not be turned on until the radiator had reached a minimum temperature. With optimization of parameters, it is felt that a generator can be started up from a cold equilibrium in approximately five minutes with each cesium reservoir heater consuming approximately one to two watt hours.

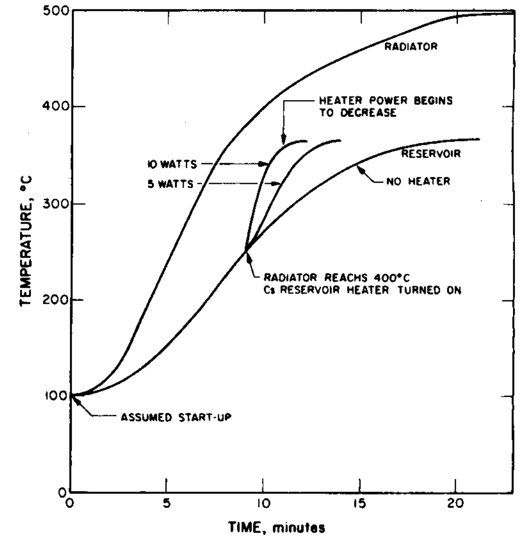
11. POWER CONDITIONING AND CONTROL

A block diagram of the recommended power conditioning and control subsystem is shown in Fig. 11. An electrochemical storage system is assumed with suitable charging provisions.

The output from the generator(s) is converted to a nominal bus voltage through a low voltage DC/DC converter network. As shown, the failure of a single converter does not mean the failure of the entire series string if multiple DC/DC converters (with shunt diodes) can be used. The evaluation of the number of DC/DC



Block Diagram of Recommended Control System



CESIUM RESERVOIR CONTROL

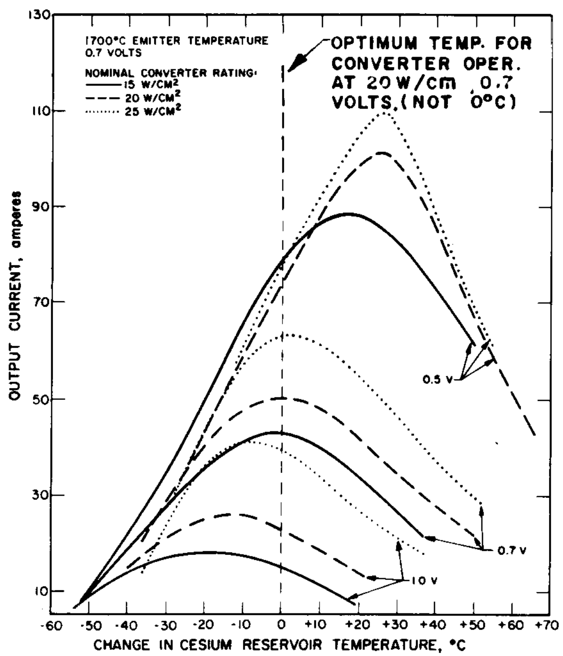


FIG. 10 - CESIUM RESERVOIR CONTROL

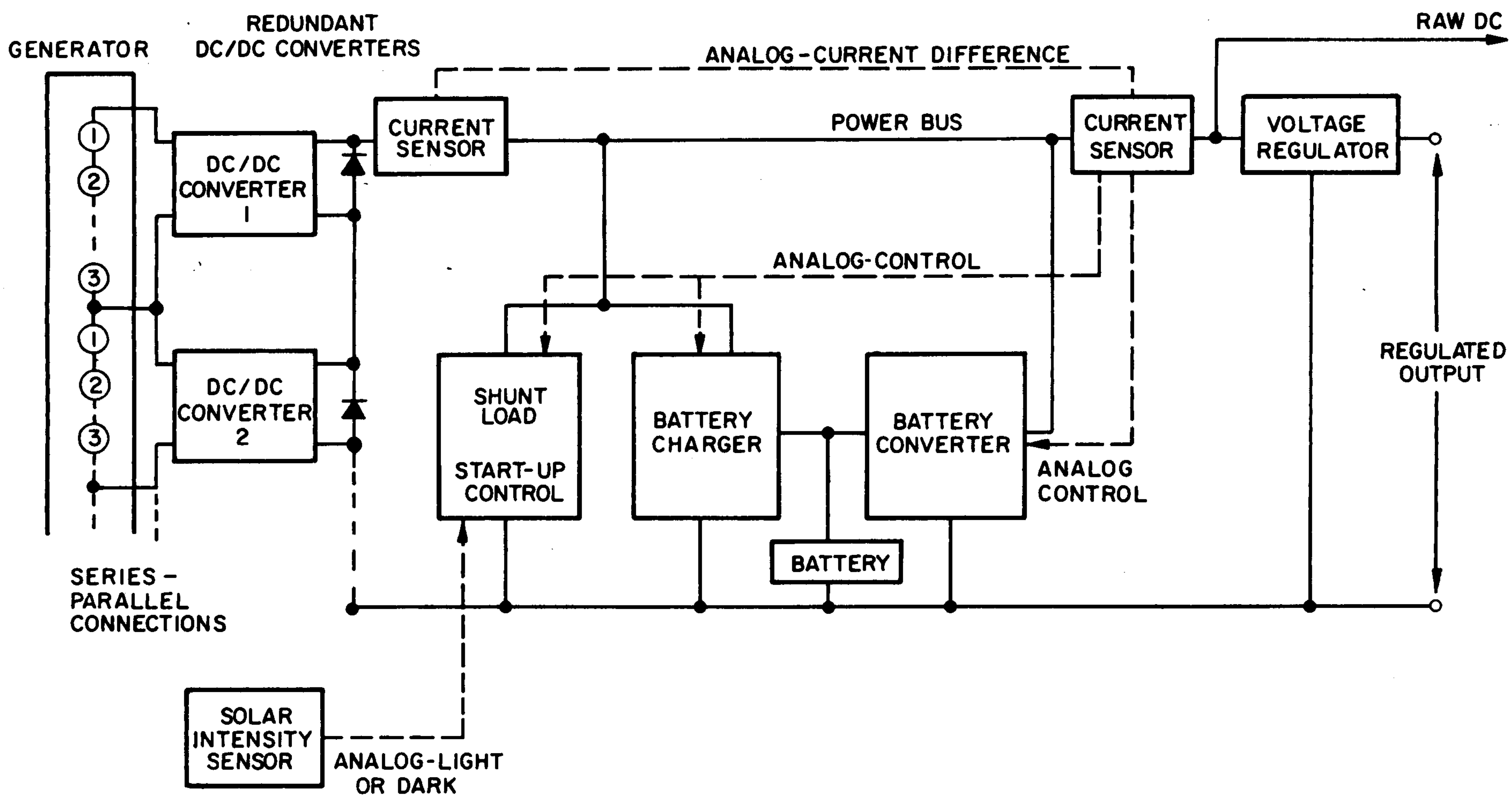


FIG. 11 - BLOCK DIAGRAM OF RECOMMENDED POWER CONDITIONING AND CONTROL SUBSYSTEM

converters and the parallel-series arrangement is a function of converter efficiency, weight, lead requirements, bus voltage requirements and other parameters.

The current output from the generator(s) is regulated by a shunt load. Current regulation was chosen due to the large losses anticipated in a voltage control system and the ability to more closely regulate the output of the generator. For reliability and prevention of overheating, it is considered essential to maintain a generator current output within close tolerances to the design point. The shunt load also has provisions for short-circuiting the generator at start-up until the diodes have opened.

A battery charger is provided for the DC storage subsystem. The charger will regulate battery charge rate and be controlled by a current limiter, maximum charge voltage, temperature and ground command. The output from the generator not used by the vehicle load will be used to charge the battery and/or dissipated in the shunt.

Battery output is converted by a high voltage DC/DC converter. During peak load requirements, when generator output is less than load demand, the charger and shunt load are disconnected electrically and the excess power requirement is obtained from the battery. The battery converter is activated when the current to the load becomes equal to the current from the generator as detected by the current sensors. The output of the battery converter is proportional to the difference between the load and generator current.

The regulated voltage output from the system is provided by a voltage regulator.

Efficiency of the power conditioning and control system, including DC/DC conversion is estimated to be nominally 70 percent, exclusive of storage. The design of the circuitry is relatively straight forward with the exception of the low voltage DC/DC converter. The major problem areas are:

1) Efficient design of the DC/DC converter with minimum weight

2) The development of a DC/DC converter which can operate at medium or high temperatures (60 to 150° C) with high efficiency.

3) The establishment of the proper tradeoff between a large number of DC/DC converters for reliability and redundancy and the weight penalty incurred through lead losses, DC/DC converter weight, etc.

12. VEHICLE INTEGRATION

The considerations in the integration of solar-thermionic systems into practical vehicles and missions are similar in many respects to those of integrating photovoltaic systems. A list of general considerations is given in Table II for illustrative purposes. The solar-thermionic systems analysis did not consider the vehicle interactions in detail; however, they must be considered in definitive flight studies.

Of special concern to solar-thermionic electrical power systems is the ability to package the system and the tradeoffs concerning number of concentrators, system performance and reliability. Figure 12 illustrates the limitations on concentrator diameter imposed by system efficiency, power output and solar intensity. Figure 13 illustrates the number of concentrators required to produce an electrical power output from the system up to 4000 watts assuming a system efficiency of 13.5 percent and a distance from the sun of 1 AU.

TABLE II

MAJOR CONSIDERATIONS OF VEHICLE INTEGRATION EFFECTS

SOLAR-THERMIONIC DESIGN

I. STRUCTURAL ASPECTS
1. Packaging
   a. Ability to fit within shroud (with adequate clearance) - static and dynamic shroud envelope.
   b. Number of attachments, linkages, dampers, etc., required and their placement on vehicle frame to provide support during launch.
   c. Support position requirements and interface with antenna and other vehicle equipment - open truss and/or monocoque bus and superstructure.
   d. Ability to have access to vehicle for ground checkout, etc., after packaging.
   e. C.G. location from launch to deployment.
   f. Ability to provide entire power system on common mounting assembly.
2. Deployment Mechanics
   a. Effect on vehicle inertial characteristics - nature of mass movement
   b. Interference with other vehicle equipment.
   c. Number of commands and complexity of unfolding sequence.
   d. Pyrotechnic design.
   e. Need for jettison of modules.
3. Dynamics of Deployed Structure
   a. Undamped natural frequencies and the matching between sources - interaction with attitude control.
   b. Damping ratio of the solar-thermionic system and matching between systems.
   c. C.C. location envelope and C.G. variation envelope.
   d. Center of radiation pressure envelope.
   e. The effects of vernier control on concentrator movement. (One or ... degree of freedom on the above.)
   f. Separation dynamics and acceleration forces and direction.
   g. Mid-course maneuver acceleration forces and direction.
   h. Terminal maneuver acceleration forces and direction.
4. Support for Other Equipment
   a. Celestial, sun or other sensors.
   b. Gas jets, solar vanes for attitude control.
   c. Antennas.
5. Obstruction
   a. Exhaust plume of attitude control, maneuver motors.
   b. Interference with fields of view of sensors or scientific instruments.
   c. Antenna obstruction.
6. Reflected Radiation
   a. Interference with sensors due to thermal radiation or reflected sunlight.

II. THERMAL ASPECTS
1. Effect of thermal radiation field on vehicle temperature budget - during cruise; transients during non-sun oriented mode.
2. Conduction of heat into vehcile through leads.
3. Power dissipation internal to vehicle.
4. Need for active (or passive) temperature control to handle above.

II. ELECTRICAL ASPECTS
1. Power requirement and profile.
2. Harness and connector requirements - framework required, resistance criteria, thermal criteria, etc.
3. Nature of output from power system - regulation, spikes, ripple, etc.
4. Nature of transient and switching, power factor, other load characteristics.
5. Possibility of electrical disconnection without mechanical disturbance for test, etc.
6. Output power level with time - allowable performance margin.

ATTITUDE CONTROL
1. Structural characteristics (see above).
2. Limit on misorientation during cruise mode for power.
3. Effect on ability to maneuver - time for acquisition, gas and power requirements, etc.

TELEMETRY AND COMMAND
1. Number and frequency of commands needed to operate system.
   Example: Battery charging instructions
   Start-up commands
   Solar flux control commands
2. Telemetry needed for operation, command, monitoring.

TEST AND CHECKOUT
1. Ability to interchange modules (such as generators) without damaging mechanical integrity of spacecraft or performance.
2. Ability to test after integration with spacecraft.

MAGNETIC DESIGN CRITERIA
1. Magnetic - static and dynamic flux limits, stability characteristics.
2. Location of critical components.

RF INTERFACE DESIGN CRITERIA
1. Location of critical components.
2. Shielding limits.

IX. CONTAMINATION
1. Evaporation.
2. Contamination from attitude control, terminal propulsion.

COMMUNICATION SYSTEM
1. Antenna pattern interference.

MISSION AND ENVIRONMENT
1. Acceleration.
2. Vibration spectra.
3. Acoustic spectra.
4. S/C roll and pitch profile.
5. Firing window and period, launch azimuth range.

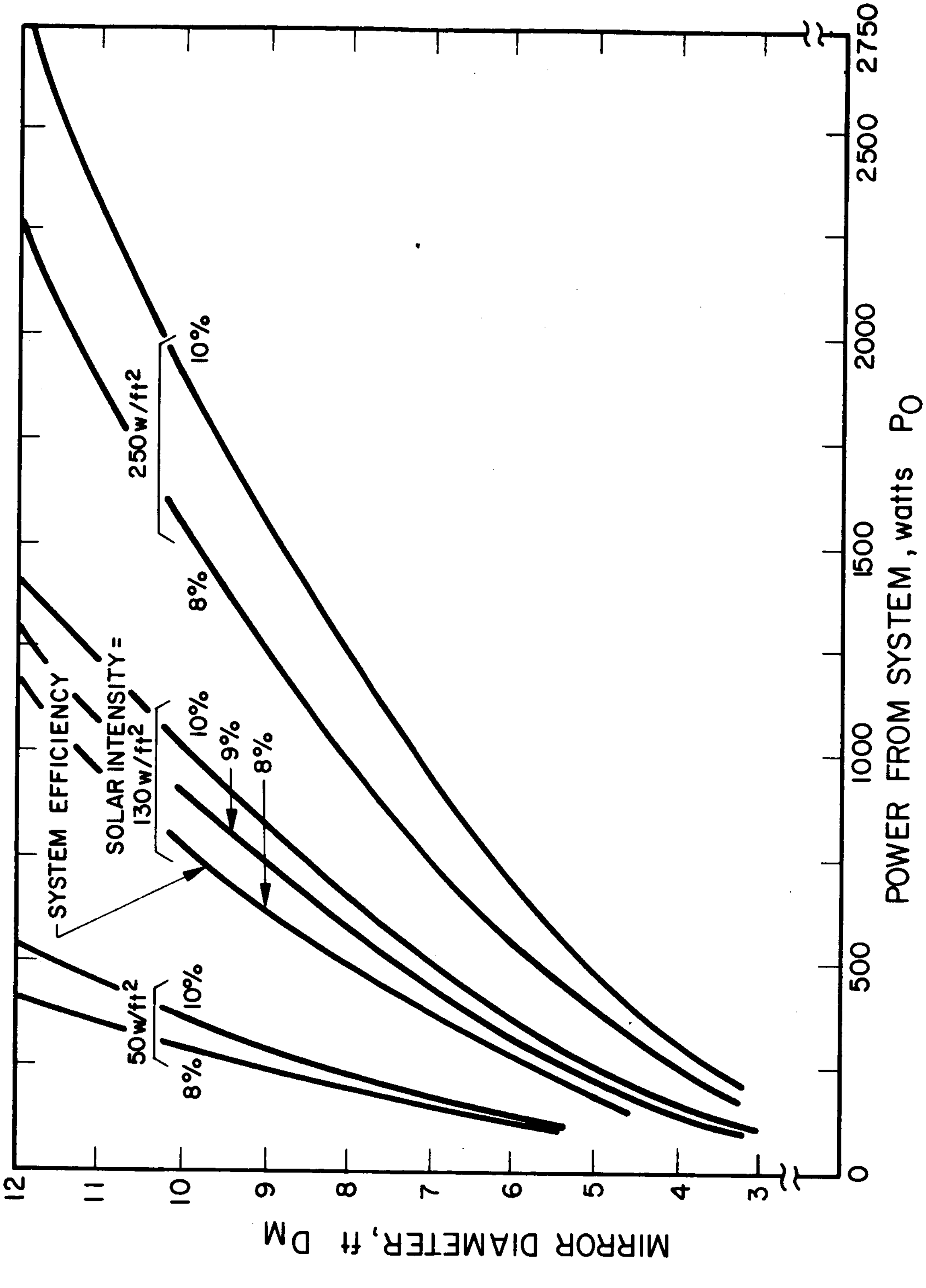


FIG. 12 - MIRROR DIAMETER VS SYSTEM POWER

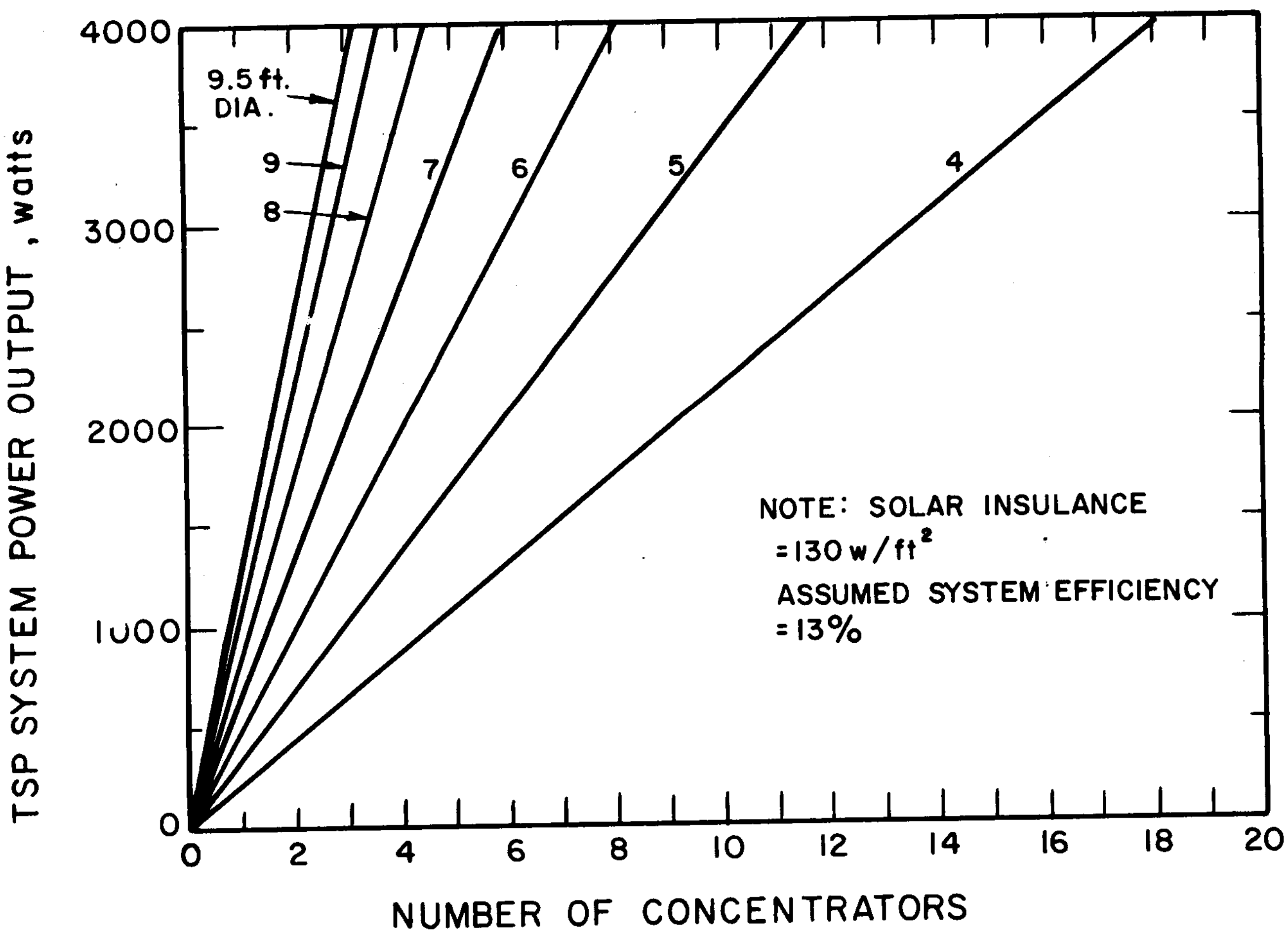


FIG. 13 - SYSTEM POWER VS NUMBER OF MIRRORS - TYPICAL CASE